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CENTER FOR HIGH ENERGY FORMING

TWENTY-FIRST QUARTERLY REPORT
OF TECHNICAL PROGRESS

Jimmy D. Mote

October 1, 1970

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172

Martin Marietta Corporation
Denver Division
Contract DA 19-066-AMC-266(X)
The University of Denver
Denver, Colorado

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ABSTRACT

This report summarizes results during the period 1 July through 30 September 1970:

a. Measurements of dynamic loads on an explosive forming die;

b. Application of explosive welding to hardware configurations;

c. Flange buckling of explosively formed domes;

d. Cylindrical explosive forming dies;

e. Explosive forming of domes in vented dies;

f. Explosive forming of domes for ground based pressure vessels;

g. The edge pull-in of explosively formed domes;

h. Fracture toughness of explosively formed high ctrength steels;

i. Explosive welding;

j. Explosive powder compaction;

k. Explosive forming of thick walled domes;

l. Theoretical studies of explosive energy transfer to a thick walled cylinder using a radial piston;

m. Explosive autofrettage of forging dies;

n. Explosive thermomechanical processing.

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I. MARTIN MARIETTA CORPORATION

1. Measurement of Dynamic Loads on an Explosive Forming Die

Principal Investigators: L. Ching, D. Bouma

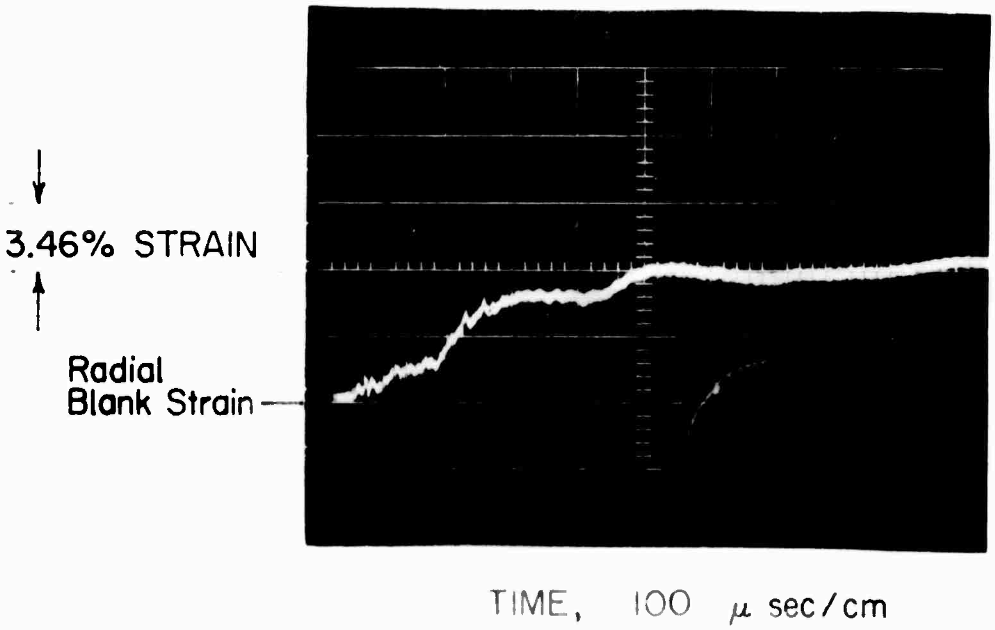
In measuring simultaneous strain-time histories of the blank and the die, it was observed that the blank strain came to an abrupt halt at the end of the forming cycle. An example of this was shown as raw data in the Fifth Annual Report of the Center for High Energy Forming. The blank strain history was similar at two radial strain gage locations while forming .063 inch thick aluminum domes in one shot with an 80 grain charge of Composition A-3. In the forming cycles the final forming strain rates were about 1000 to 1400 per second just prior to the strain halt caused by impacting the die contour. This occurred at a time of 0.8 msec after detonation. This observation of abrupt strain rate charge would indicate that the reloading energy to the blank was prematurely interrupted by impacting the die contour. To explore this further, the same test was conducted with the charge size reduced 25%. The results in Figure 1 show the blank and die strain time histories to be similar to the full charge size test with one exception. The very high strain rate just prior to the final strain of the formed contour did not appear on the 75% charge load. From these tests alone it would appear that reloading does not greatly effect die strain. This supports a previously reported conclusion, but the apparent appearance and disappearance of the reloading phenomena may be noteworthy for consideration for further tests.

2. Application of Explosive Welding to Hardware Configurations

Principal Investigator: W. Simon

Weld of .007 in. Stainless Steel (321) to Titanium

One of the problems in welding foil is that the explosive force required is so low that for a conventional seam weld, .015 in. Detasheet must be used. The handling problem with the thin Detasheet is severe, and thus the set-up time is fairly long. The non-uniform pressure field associated with explosive cord suggested that it might be possible to weld foil with .084 in. diameter Detaflex. The edge of the foil was rolled up about 30° on an approximately 1/16 in. radius and the Detaflex installed in the radius. Figures 2 and 3 show 5X and 200X views of the weld. Handling of the cord is easy and set-up time much reduced. As shown by the figures, an excellent weld is obtained.



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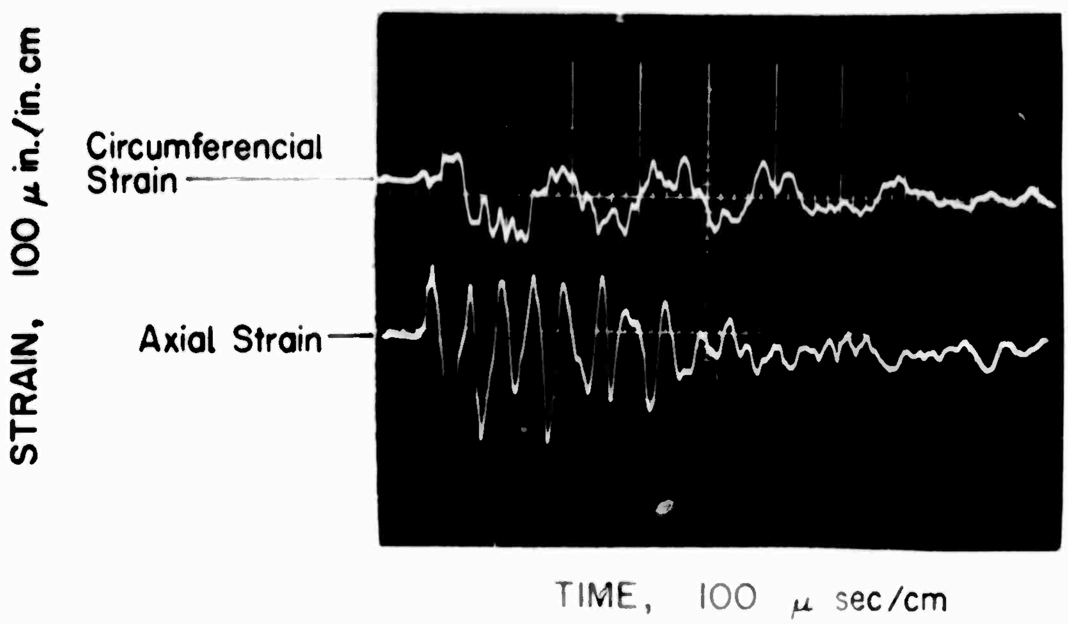

DIE

Figure 1 Raw Data - Simultaneous [illegible] - [illegible] A-3 - [illegible] Stress Die

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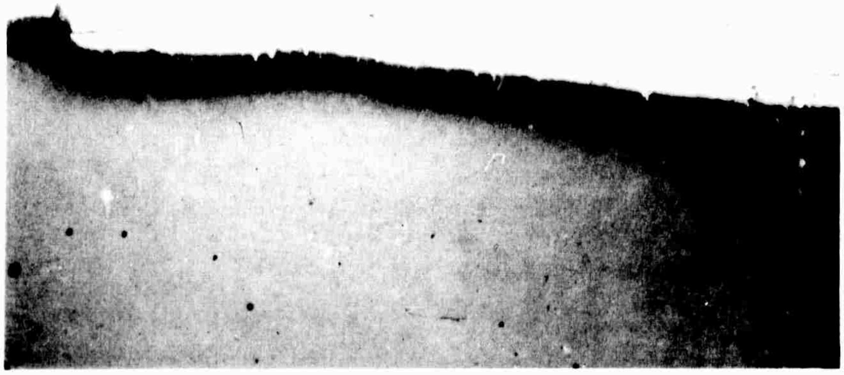

Figure 2 5X photo of .007 in. Stainless Steel (321) Welded to Titanium

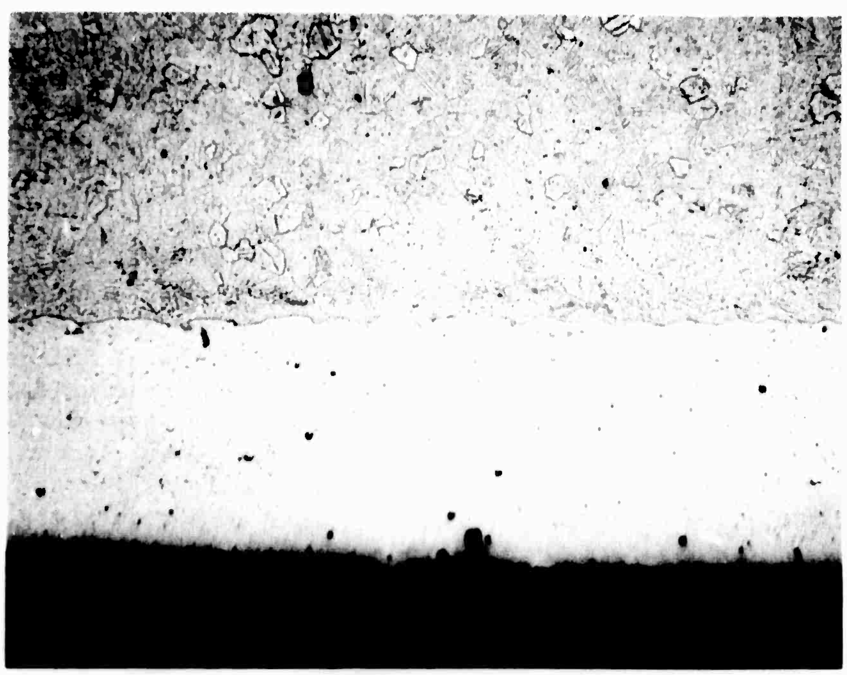

Figure 3 200X photo of .007 in. Stainless Steel (321) Welded to Titanium

II. UNIVERSITY OF DENVER

1. Flange Buckling of Explosively Formed Domes

Principal Investigator: M. A. Kaplan

Graduate Student: H. Boduroglu

The stability analysis for the flange is almost completed. The analysis has been formulated in terms of energy principles. It has been assumed that the flange undergoes small out-of-plane bending consistent with the given geometrical boundary conditions, and that this bending occurs without stretching of the middle plane. When the incremental work, done by the forces necessary to produce continued in-plane deformation, becomes greater than the incremental work to produce lateral deflection, the plate is unstable and buckling occurs. The effects of the rubber annular rings in the clamping system have been included in the incremental work done by the lateral load at the onset of buckling.

The Rayleigh-Ritz Method is being used to determine the buckling parameter D, the "pull-in" at the outer edge. The problem reduces to finding the smallest root of the equation $F(D) = 0$ for a given value of clamping pressure. The problem has been programmed in Fortran IV.

The theoretical values which have been obtained thus far appear to be reasonable.

Static tests are being planned to provide data with which to validate the predicted results. Dynamic testing (by explosive forming) is not suitable since the number of tests required to determine the onset of buckling would be prohibitive.

2. Cylindrical Explosive Forming Dies

Principal Investigator: R. Knight

Data has been obtained on the strain in the workpiece until contact with the die using the new adhesives and surface preparation techniques. These records do not show the abrupt change in strain rate which was observed in the records when the gages failed. The change in strain rate is felt to have been an apparent change due to the failure of the strain gages. A continuing effort has been underway to develop the analysis to predict the strains and motion in the system more accurately.

3. Explosive Forming of Domes in Vented Die

Principal Investigator: A. Ezra

Graduate Student: P. Hardee

In the last quarter several attempts have been made to get the pressure time history of the gas between the die and the blank during the forming process. There have been problems with the mechanical vibration of the pressure transducer, the mechanical shock transmitted to the transducer causing structural damage to the equipment and with determination of a range of material and explosive parameters within which to work. A shock mount has been constructed to isolate the pressure transducer from the mechanical shocks and also from the high frequency transient vibrations associated with the natural resonance of the die.

One item of note is that during one of the preliminary tests the newly constructed die was used. This die had a porosity of 5%. A blank constructed of 5051 H32 Aluminum 1/8 inch thick was used. It formed all the way to the bottom of the die and struck with sufficient force to mark the holes in the die on the surface of the blank.

4. Explosive Forming of Domes for Ground Based Pressure Vessels

Principal Investigator: L. Alting

Graduate Student: R. Aderohunmo

The goal for this project is to develop a new industrial dome forming process which gives minimum material waste and incorporates the simplest die design possible. The desired dome shapes correspond to ASME Standards.

In free forming we succeeded after a number of experiments in getting the right shape and the blank diameter was then minimized. The smallest blank to diameter ratio for both $D/_t$ = 160 and 200 was found to be about 1.17. To get the final head shape we need further to form a cylindrical skirt. This can be done in different ways.

a. Deep drawing operation.
b. Inside rolling.
c. Explosive bending.

The deep drawing operation works but the process acquires pressing equipment and a punch system which can be expensive.

The inside rolling is carried out while the dome is still in the die with one or another roll system so that the outer part of the dome is pressed against the upper cylindrical part of the die ring.

The explosive skirting is carried out by placing the dome on a punch and loading the flange with explosives so that the detonation will bend it down to form a cylindrical part.

These three methods are being investigated at present.

A quite different approach has also been tested. Here we chose relative high blank to diameter ratios (1.25 - 1.50) and tried to get the final shape with a cylindrical skirt by shooting the same dome twice. These few experiments indicate the process is feasible.

Which of the two approaches is the best will depend on several factors and both ought to be fully explored.

5. <u>The Edge Pull-In of Explosively Formed Domes</u>

Principal Investigator: M. Kaplan

Graduate Student: S. Kulkarni

The analysis to predict the edge pull-in of explosively formed domes is based on the rate of work approach. It assumes:

a. apriori knowledge of the shape of the deformed blank and,
b. a velocity field, in terms of arbitrary constant, compatible with the geometrical conditions of the problem.

The total rate of work of the system is formulated and minimized with respect to these constants to determine the mechanical state of the deformed part.

The numerical results are found to agree closely with certain of the explosive forming test results. In particular, the thickness strain distribution in the dome and the flange are in very good agreement with the experimental results.

The predicted thickness strains and stresses for a clamped blank are also in close agreement to that predicted by the hydrostatic bulge test analysis of Dr. Thurston.

Presently, work is being continued to determine the entire strain field from the strain rate distribution.

6. <u>Fracture Toughness of Explosively Formed High Strength Steels</u>

Principal Investigator: H. Otto

Graduate Student: R. Mikesell

Charpy impact tests were conducted on explosively formed and cold rolled 4130 and 4340 after heat treatment and tempering at 600°F. The amount of effective strain for both deformation modes was approximately the same. They were as follows: 4130 explosively formed $\epsilon^* = 0.0635$, cold rolled $\epsilon^* = 0.0786$; 4340 explosively formed $\epsilon^* = 0.0587$, cold rolled $\epsilon^* = 0.065$. Heat treatments and resulting hardnesses are presented below:

Steel	Austenitizing Temperature, °F	Quenching Media	Tempering Temperature, °F	Hardness, R_c
4130	1600	oil	600	46
4340	1500	oil	600	47

After heat treatment, the blanks were ground to remove all decarburized layers. Since the starting stock was 1/4 in. thick, subsize Charpy specimens were used. Lengths and widths were held constant at 2.5 and 0.393 in., respectively. The thickness was 0.145 in. and 0.167 in., respectively, for the 4130 and 4340 steels.

Results of the impact tests are presented in Tables 1 and 2 and the graphical results are shown in Figures 4 and 5. In examining the results, no overall trends are observed, with each steel responding differently. The scatter in data for the 4130 steel indicates little difference in impact response between the explosively formed and cold rolled steel after heat treatment. The increase from minimum to maximum energy absorbed occurs over a range of about 110°F with a ductile to brittle transition temperature at about 0°F. At higher temperatures, the energy to fracture appears to be slightly higher for the explosively formed steel.

Table 1. Results of Impact Tests on 4130 Steel

Cold Rolled Stock

Test Temperature, °F	Impact Strength, ft. lbs.	Type of Fracture
72	5.0	Brittle-Ductile
37	4.0	Brittle-Ductile
27	4.0	Brittle-Ductile
1	4.8	Brittle-Ductile
-33	3.8	Brittle
-73	1.5	Brittle

Explosively Formed Stock

Test Temperature, °F	Impact Strength, ft. lbs.	Type of Fracture
72	7.8	Brittle-Ductile
72	6.0	Brittle-Ductile
53	6.8	Brittle-Ductile
37	5.8	Brittle-Ductile
27	6.1	Brittle-Ductile
4	4.3	Brittle-Ductile
-33	2.8	Brittle
-124	1.8	Brittle

Table 2. Results of Impact Tests on 4340 Steel

Cold-Rolled Stock

Test Temperature, °F	Impact Strength, ft. lbs.	Type of Fracture
72	5.8	Brittle-Ductile
44	6.7	Brittle-Ductile
14	3.9	Brittle-Ductile
-61	4.0	Brittle
-136	2.8	Brittle
-242	1.7	Brittle

Explosively Formed Stock

Test Temperature, °F	Impact Strength, ft. lbs.	Type of Fracture
72	7.2	Brittle-Ductile
44	6.9	Brittle-Ductile
14	5.2	Brittle-Ductile
-24	6.0	Brittle-Ductile
-26	5.6	Brittle-Ductile
-136	4.1	Brittle
-242	3.0	Brittle
-320	1.8	Brittle

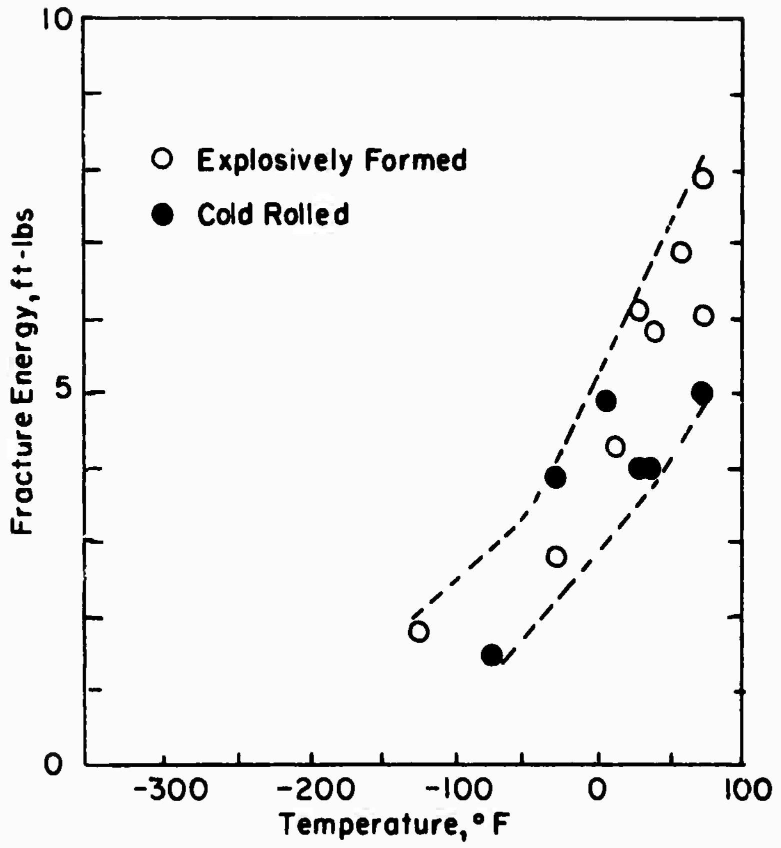

Figure 4. Ductile to Brittle Transition Relationship for Explosively Formed and Cold Rolled 4130 Steel Heat Treated after Deformation. (600°F Temper)

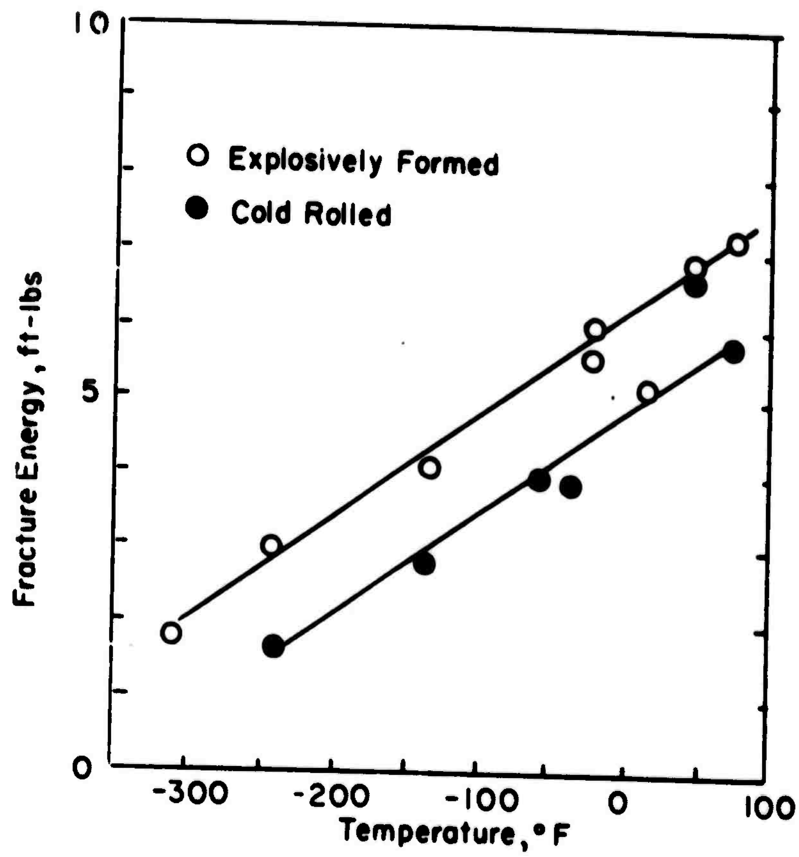

Figure 5. Ductile to Brittle Transition Relationship for Explosively Formed and Cold Rolled 4340 Steel Heat Treated after Deformation. (600°F Temper)

No ductile to brittle transition temperature is discernible for the 4340 steel. A linear increase in energy to fracture is observed as the test temperature increases. Some difference does exist between the explosively formed and cold rolled 4340 in that the energy to fracture of the explosively formed stock is slightly higher.

Tensile strengths of both the 4130 and 4340 were on the order of 240,000 to 250,000 psi. The trend observed for the Cr-Ni-Mo series steels (43xx), in that a gradual increase in impact strength with increased temperature occurred, is consistent for the 4340 steel in the condition tested. The 4130 steel, which has a mixed martensitic-bainitic structure with a larger grain size than the 4340, would have a more marked and lower transition temperature as is observed in these tests.

Impact tests on stock tempered at 1000°F and as-formed steel are currently underway.

Fracture toughness tests were conducted on the 4130 and 4340 steels that had been explosively formed and heat treated. The heat treatment was the same as that given the specimens used for Charpy impact testing. A specimen measuring 1.0 x 0.20 inches in cross section was used. Pop-in occurred at the ultimate in both steels.

Fracture of the specimens was in plane strain and the K_{IC} was calculated from the formula

$$K_{IC}^2 = \frac{1.21 \pi \sigma^2 a}{\phi^2 - 0.212 \left(\frac{\sigma}{\sigma_{ys}}\right)^2}$$

where:

σ = tensile strength

a = 1/2 minor axis of semi-elliptical crack

ϕ = elliptical function =

$$\int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{c^2 - a^2}{c^2}} \sin \theta d\theta$$

σ_{ys} = yield strength (0.2% offset)

The above expression is based upon the assumption that the initial fatigue crack is in the shape of an ellipse.

Results of the fracture toughness studies are presented below.

4130 Steel

Specimen	Specimen Orientation(1)	K_{IC} psi (in.)$^{1/2}$	Forming Strain (ϵ_f^*)%
As-received	Longitudinal	69.8	---
		67.5	---
As-received	Transverse	77.8	---
		78.1	---
Formed	Longitudinal	70.3	4.48
		74.7	4.48
Formed	Transverse	83.3	3.94
		85.0	3.94
	4340 Steel		
As-received	Longitudinal	84.1	---
		86.4	---
As-received	Transverse	77.3	---
		78.8	---
Formed	Longitudinal	81.5	4.15
		80.7	4.15
Formed	Transverse	70.5	4.30
		72.0	4.30

(1) With respect to original rolling direction

The results do indicate some orientation dependence with the trends being opposite for the two steels. There is no explanation as to how orientation affects the results, especially after heat treatment.

7. Explosive Welding

Principal Investigator: S. Carpenter

Graduate Students: M. Nagarkar, R. Wittman

Diffusion studies have been carried out using roll-bonded stock supplied by Texas Instruments, Inc. Welds were made using the roll-bonded material as the explosive welding stock so comparisons could be made of the two types of bonds. After explosive welding of Cu-Ni couples, samples were heated at 500°C, 750°C,

900°C, and 950°C. Diffusion zone widths were determined by electron microprobe and included the zone at all three interfaces, i.e., Cu-Ni couple serving as cladder plate; the explosive bonded Cu-Ni interface; and the Cu-Ni couple serving as the base plate. Diffusion zone width of the heat treated as-received roll bonded Cu-Ni was also measured and used as a standard of comparison. Results of the tests to date are listed in Table 3.

Analysis of the data obtained to date indicates that a wider diffusion zone is obtained at the explosive bonded interface than at roll bonded interfaces. The zone width is temperature and time dependent, with little or no diffusion occurring until a temperature in excess of 500 C is used. Detailed electron microprobe work is still underway to establish all the time-temperature dependencies.

Tensile specimens are being prepared from welded and heat treated Cu-Ni couples to determine the bond strength and establish the effect of diffusion zone width to bond strength.

Table 3. Results of Diffusion Experiments with Explosion and Roll Bonded Cu-Ni Clads

Heat Treatment		Diffusion Zone Width, inches		Difference,
Temp. °C	Time Hrs.	Exp. Bond	Roll Bond	inches
500	10	.0004	.0004	0.00
750	10	.0019	.0012	0.0007
900	10	.0028	.0022	0.0006
975	10	.0046	.0033	0.0013

8. Explosive Powder Compaction

Principal Investigator: H. Otto

Graduate Students: T. McClelland, D. Witkowsky

This program is divided into two areas, (1) an investigation of the parameters for making rolling and extrusion preforms, and (2) methods of making composites. Sintering treatments on steel powder compacted at explosive to powder ratios of 1.1:1.0, 0.84:1, and 0.64:1 have been continued. Red Cross 40% Extra dynamite was used for compacting. For the material compacted at a loading ratio of 1.1:1.0 very little difference is noted after sintering

times of up to three hours. Sintering apparently has reduced the post compacted densities of the materials compacted at loadings of 0.84:1.0 and 0.64:1.0, with the greatest change being noted at the lower loading (98.2 to 97.6% of theoretical density). The same trends were observed in specimens heat treated at 900°C at sintering time increments up to 12 hours.

A further survey has been made of the literature in an effort to determine if enough data is present to develop a relationship between the energy expended during explosive compaction and the as-compacted density of a particular material. In most instances where compacted densities are given, there is no information on the amount of explosive used.

The program on explosive compaction of composites has just been initiated. The selection of a basic experimental model has not been determined at this time.

9. Explosive Forming of Thick Walled Domes

Principal Investigator: L. Alting

Forming of thick walled components has always been - and still is - a difficult and expensive job. The goal for this project is to develop an explosive method which is simple and cheap to apply.

Explosive forming of thick walled components will normally require quite big charges which again will give hugh forces on a die system. The question therefore arises: Is a conventional die system necessary?

After some working on this idea the concept shown in Figure 6 was developed.

The difference in compressibility between water and styrofoam gives a relative strong die action. If the styrofoam is dropped, the final deflection decreases 60 - 70%.

The numbers in Figure 6 correspond to 1:12th scale model experiment to get a 12 in. in diameter hemisphere with 1/2 in. thick wall in boiler plate. Figure 7 shows a quite promising result where the final deflection is 5 in. About 100° in the nose area corresponds to a circle with 12 in. diameter.

An increased charge weight will certainly give an even better shape. The charge weight can be increased either by increasing the charge diameter or the charge thickness. As yet, we don't know which way is most efficient.

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Figure 6. Die less Forming of Domes

To obtain better shapes we further have the possibility to attach mass rings to the plate edges.

The results generally look promising and even if we can't get a perfect hemisphere, we can get a convenient and valuable preform.

Figure 7. Dome Formed in Accordance with Figure 6. Charge Weight- 436 grams, Diameter- 8 in., and Rubber Thickness- 1 in.

10. Theoretical Studies of Explosive Energy Transfer to a Thick Walled Cylinder Using a Radial Piston

Principal Investigator: H. S. Glick

Graduate Student: V. D'Souza

A computer program to give the residual stresses at the bore of a long thick walled tube subjected to an exponentially-decaying pressure-time history at its bore was checked for various decay rates and tube dimensions. The analysis assumes the tube is composed of an incompressible elastic-plastic material which does not work harden and is not rate sensitive. Axial symmetry and plane strain conditions are also assumed. The program is controlled by certain parameters which depend on: 1) the wall thickness which has reyielded, 2) the displacement of the tube, 3) the pressure on the bore, 4) the number of radial stations, and 5) the time steps for numerical integration. The sensitivity of the results to these constraints was checked and values of the parameters have been chosen which give good accuracy and require reasonable computing time. It was also checked that when there was no reyielding, the residual stress was the same as that obtained in a static autofrettage process. Also, it was found that as the number of reyield cycles increased, the residual compressive hoop stress decreased.

Since the pressure-time history on the bore of the thick walled cylinder is not of the exponential-decay type when a radial piston is employed, the above program has an option to take into account an arbitrary pressure-time history. The closed form solution for elastic unloading which holds for the exponentially decaying pressure-time history is repaced by a stepwise integration. This part of the program is being checked at present.

11. Explosive Autofrettage of Forging Dies

Principal Investigator: W. G. Howell

The technology developed in last year's program on explosive autofrettage of gun barrels is being evaluated as a process for increasing the life of certain types of forging dies in a cooperative program with Sundstrand-Denver. A die which fails due to radial tensile cracks and which is fabricated with a shrink ring to increase radial strength was selected for this study. Three 25% scale models of the die under consideration were autofrettaged and residual stresses ranging from 75,000 psi to a maximum of 117,000 psi were obtained. Full scale dies are now

being prepared by Sundstrand for explosive autofrettage by the Denver Research Institute. These dies will then be put into use at Sundstrand and statistical data will be collected to determine what increase in operational life, if any, may be expected by use of the autofrettage process.

12. Explosive Thermomechanical Processing

Principal Investigator: R. Orava

Post Doctoral Fellow: A. Dowling

Graduate Student: P. Khuntia

The effort related to the study of the relative behavior of metals subsequent to conventional and high energy rate forming is continuing. Due to the great need, expressed by a number of inquiries to this Center for terminal property data (especially for ferrous alloys) some attention is being devoted to the generation of such information. A possible large scale economic application of explosive forming is in the production of heads for pressure vessels where boiler plate is the most commonly used material. For the process of explosive forming to be accepted in this area it has to be shown that the mechanical properties of the materials are not impaired.

Therefore, specific tests will be carried out on an A-286 Grade C steel, one of the most widely used for boiler plate applications. In order for specimens to contain a representative number of inclusions, impurities or other flaws, plate which is 3/8 in. thick is being examined.

The mechanical properties of material characteristic of four forming histories will be compared: undeformed, conventionally formed, explosively free-formed, and explosively die-formed. Specimens will be stress relieved according to standard fabrication practice. Moreover, the influence of departures from this schedule, including reaustenitizing, will be investigated. To date, two blanks have been free formed under biaxial stress conditions and others have been gridded in preparation for conventional and die forming. Free forming was accomplished by means of a "clam-shell" configuration. The explosive (Detasheet) was placed between two 1 in. thick rubber cylinders which, in turn, were located coaxially between the two steel blanks. These were bolted together and immersed in water prior to detonation.

In another aspect of this program considerable emphasis is being placed on the utilization of HERF, explosives in particular for the deliberate enhancement of material properties. The approach selected involves the introduction of the explosive forming process into a thermomechanical processing (TMP) schedule for alloys hardenable by phase transformations. This technique has been denoted "explosive thermomechanical processing" or ETMP.

The following four alloys have been selected for study.

1) Semi-austenitic precipitation-hardenable stainless steel (17-7PH grade).
2) 18% nickel maraging steel (250 grade).
3) Precipitation-hardenable beta-phase titanium alloy (Beta III grade).
4) High temperature nickel-base alloy (Udimet 700 grade).

The principal investigator is grateful to J. L. Arnold of the Armco Steel Corporation for supplying the 17-7PH steel sheet, to V. C. Retensen of Crucible, Inc., for the Beta III titanium, and E. W. Kelley of Cabot Corporation for the U-700.

A new rectangular stretch forming die has been designed and fabricated. This will be used for the ETMP studies. Blanks of dimensions up to 7 in. x 10 in. can be accommodated. The use of rectangular blanks considerably reduces the material requirements and preparation costs compared with those needed for forming domes. Moreover, tensile fatigue, and notch tensile specimens without curvature can be extracted from the product thereby excluding any flattening operation.

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TWENTY-FIRST QUARTERLY REPORT OF TECHNICAL PROGRESS - THE CENTER FOR HIGH ENERGY FORMING
Mote, J. D., Martin Marietta Corporation - University of Denver, Denver, Colorado
Report No. AMRA CR 66-05/26, October 1, 1970

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a. Measurements of dynamic loads on an explosive forming die;

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f. Explosive forming of domes for ground based pressure vessels;

g. The edge pull-in of explosively formed domes;

h. Fracture toughness of explosively formed high strength steels;

i. Explosive welding;

j. Explosive powder compaction;

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l. Theoretical studies of explosive energy transfer to a thick walled cylinder using a radial piston;

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Mote, J. D., Martin Marietta Corporation - University of Denver, Denver, Colorado
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